

A Multidimensional Approach to Understanding the Development of Design Skills, Knowledge, and Self-Efficacy

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Abstract

This complete research paper reports on how realistic design challenges might support first year students to develop knowledge, capacity, and self-efficacy in designing.

Theory suggests self-efficacy and learning are linked, and importantly, that implicit knowledge (i.e., knowing how) and explicit forms of knowledge (i.e., knowing that) develop differently. While many first year courses include design challenges, not all challenges support students to develop knowledge about, capacity to, and self-efficacy for designing. We sought to investigate how realistic design challenges might support growth in these areas, compared to a baseline group in a first-year chemical engineering course at a Hispanic-serving research university in the southwest United States. Students completed measures of design self-efficacy, explicit design knowledge, and implicit design framing knowledge as a pre/post course measure. Using exploratory factor analysis, we identified two explicit design knowledge factors ill-structuredness and framing. Using repeated measures ANOVA, we found that students in both baseline and implementation groups reported moderate design self-efficacy, with post-course scores slightly but significantly higher. No difference was found by group or timepoint on students' explicit knowledge of design. Compared to the baseline, the implementation group showed more growth in implicit design knowledge. Taken together, this could suggest differences in the rates of change in implicit and explicit growth. The results suggest first-year students can learn to design before they acquire knowledge about design.

Introduction

Research Purpose

First-year design courses and challenges have been increasingly common in engineering. Those who teach such courses often contend with high enrollments and limited supports. Under these conditions, it is not surprising to find variability in whether design experiences support students to develop knowledge about, capacity to, and self-efficacy for designing. Simple design challenges that don't require students to frame problems may artificially inflate students' self-efficacy and contribute to misconceptions about designing.

In general, self-efficacy and learning are linked, and importantly, that implicit knowledge (i.e., knowing how) and explicit forms of knowledge (i.e., knowing that) develop differently.

In particular, we sought to answer the following research questions:

1. To what extent do realistic design challenges affect students' design self-efficacy and explicit design knowledge?
2. In what ways do first year students approach framing design problems?
3. Compared to a baseline group, how do first year students who have experienced realistic design challenges approach framing design problems?

Design Self-Efficacy

Self-efficacy theory posits that increased experience fosters greater confidence (self-efficacy), which in turn supports learners to cope with increasingly difficult material [1]. Much of the early research on self-efficacy in engineering focused on academic self-efficacy. Such studies aligned to findings in other fields, including that women tend to report lower self-efficacy than men [2] and that opportunities to participate in academic extracurricular activities correlate with higher academic self-efficacy [3]. Learning experiences that focus on mastery appear to increase academic self-efficacy [4].

Research has also focused on more contextualized views of self-efficacy, using measures of students confidence related to specific aspects of completing an engineering degree. This form of engineering self-efficacy explains variance in GPA, but may decline over the course of the first year [5], or come into alignment with skill level as they get feedback about actual performance [6]. Carberry, et al. [7] developed a measure of design self-efficacy based on models of engineering design process. Design self-efficacy is a distinct construct from other forms of engineering self-efficacy [8]. First year students who completed a design challenge showed higher design self-efficacy compared to those who had not [9], and students who participated more in design challenges reported lower anxiety about designing [10]. Recent research identified that students reporting higher design self-efficacy tended to score higher on a measure of creative design solutions [11]; this suggests a relationship could exist with design framing skills as well, given theorized linkages between problem framing and creativity [12].

Explicit Design Knowledge and Implicit Design Practice

Research from cognitive and learning sciences has long demonstrated differences between implicit knowledge (i.e., knowing how) and explicit knowledge (i.e., knowing that) as well as in their development [13, 14]. In the context of engineering design, explicit knowledge includes understanding the nature of design as an ill-structured, iterative process to identify and address needs without violating constraints, as well as knowing *about* common procedures and their intended purposes—e.g., ideation should be used to produce more creative design solutions [15-17]. Implicit design knowledge includes the capacity to direct such procedures, including how and when to use them, in light of the ambiguity of ill-structured design problems [18]. Therefore, much of design problem framing is implicit.

Previous research has contrasted novices and more experienced designers to understand how experience impacts capacity to design and quality of design work; both reflect a combination of explicit and implicit design knowledge. More experienced designers produce better designs, and this may be due to their early efforts to frame the problem [19]. For instance, seniors, compared to first-year students, gather more information, work in a more iterative fashion, consider a broader problem space, and generate more solution ideas [19-21]. This suggests differences in implicit design knowledge.

Research on the impact of design education suggests differences in gains on implicit and explicit forms of design knowledge. While first-year students easily developed an understanding of the role of ideation (explicit design knowledge), they did not develop an understanding of problem framing (implicit design knowledge) [22]. However, whether this is a developmental or instructional issue is not clear, though the research on experienced designers suggests that the development of implicit knowledge requires many opportunities to practice, an insight backed by

research on how people learn [13, 14]. Thus, attention to the kinds of design experiences that build implicit design knowledge may provide new insight into the professional formation of engineers.

Significance of the Current Study

Across these studies, it appears that experience can support students to report self-efficacy that better aligns to their actual abilities and that they may make gains in explicit knowledge at rates that differ from implicit knowledge. Yet, implicit knowledge is arguably more important. Past research has focused on measures that conflate implicit and explicit knowledge, suggesting the need for studies to consider these in more independent forms, and in particular, linked to instruction. We address these gaps by studying multiple sections of a first year chemical engineering course, considering pre- and post-measures of design self-efficacy, and implicit and explicit measures of design knowledge.

Methodology

Participant Recruitment and Study Setting

Following IRB approval, we recruited students enrolled in sections of a first-year chemical engineering course from 2015 to 2018 at a Hispanic-serving research university in the Southwest United States (Table 1).

Table 1. Sample size based on number of completed design skills tests by semester. Note that the number is lower when linked to survey data.

Year and semester	Educational intervention	Pre (n = 286 [†])	Post (n = 237 [†])	Pre/post (n = 208 [†])
Fall 2015	Lectures, lab activity	n = 86	n = 67	n = 60
Spring 2016		n = 26	n = 15	n = 15
Fall 2016	Sequence of realistic design challenges (Table 2)	n = 53	n = 39	n = 36
Spring 2017		n = 41	n = 33	n = 30
Fall 2017		n = 38	n = 41	n = 26
Spring 2018		n = 48	n = 42	n = 41

[†] Some students enrolled in the first-year course more than one time. They are included in course counts, but not in the total.

Students in the first two semesters who did not receive realistic design challenges represent a baseline. Originally, the first-year course included technical lectures by departmental faculty, a brief lab experience, and a team-building experience. In subsequent years, the course included a sequence of realistic design challenges created specifically to be authentic to students' experiences and accessible, yet reflective of professional practice (Table 2).

Table 2. Realistic design changes completed by first-year students in the redesigned course

Challenge	Description
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Antimicrobial entrepreneurial challenge	Students propose applications of a novel antimicrobial material based on their own experiences with and knowledge of bacterial hazards. They conduct a simple market analysis and pitch their ideas, including how their design will improve lives. Examples include paper money cleaning systems, make-up brushes, and toys for children in hospitals.
Evaporative cooling water bottle research-based challenge	Students build on regional practice of using evaporative cooling to design a self-cooling water bottle. They conduct an experiment to determine how wetting a thin cotton muslin wrap can cool a water bottle. They create their own design for a self-cooling water bottle they could use on a hike, employing evaporative cooling, and test it in the lab. They compare their results in a short report and create a simple market plan.
Acid Mine drainage community-based challenge	Students investigate the 2015 spill (and ongoing leakage) of acid mine drainage in the Animas river. They choose a specific rural community, propose a community engagement strategy, develop a prevention or emergency response water filtration system, and deliver an oral presentation (pitch) of their designs.

Data Collection and Analysis Techniques

All students enrolled in the course were asked to complete all study measures as part of normal course assessment. Our study sample only includes those who provided consent. All measures were completed as pre-/post- course measures. This includes a survey, completed out of class and online, to measure their design self-efficacy and design knowledge, as well as an in-class design skills test (DST) to measure their implicit design knowledge.

Design Self-Efficacy & Design Knowledge Survey

Students rated their agreement (1 = Strongly disagree to 5 = Strongly agree) to six items on design self-efficacy. We drew questions from a previously-developed measure of engineering design self-efficacy [7]. Each Likert item begins with the same stem, “I am confident I could...” followed by a specific engineering design practice, such as “construct a prototype” and “evaluate and test a design solution.” We omitted two holistic items and one item focused on communication.

Students rated their agreement (1 = Strongly disagree to 5 = Strongly agree) to 17 items measuring explicit design knowledge, drawn from studies of expert views of design process [15]. We performed an exploratory factor analysis (EFA) with promax rotation to identify the factor structure of the survey. We eliminated low loading and cross loading items. We identified three factors with higher reliability, including one factor related to design self-efficacy ($\alpha=.89$) and two explicit design knowledge factors—ill-structuredness ($\alpha=.86$) and framing ($\alpha=.70$) (Table 3).

Table 3. Three factor solution

Survey Items	Factor 1	Factor 2	Factor 3	Mean	SD	Alpha if item deleted
<i>Design Self-Efficacy: I am confident I could an authentic engineering design problem</i>						
develop possible design solutions to	0.861	-0.011	-0.004	3.81	0.96	0.86
evaluate and test a design solution	0.841	-0.019	0.049	3.49	1.04	0.85
construct a prototype for	0.829	0.006	-0.073	3.57	1.03	0.86
select the best possible design for	0.757	-0.036	-0.002	3.76	0.98	0.87
identify a need in	0.746	0.016	0.029	3.50	1.03	0.87
describe the work professional engineers do.	0.515	0.034	0.024	3.93	0.91	0.9
<i>Design knowledge: Design problems are ill-structured</i>						
Design is usually a linear, predictable process	0.008	0.908	-0.016	2.90	1.49	0.78
An expert designer is usually right on the first try when designing	0.020	0.868	0.020	3.00	1.60	0.78
Designers of equal skill and experience should come to the same design solution given the same initial design problem	0.029	0.812	0.020	2.93	1.55	0.81
Design problems have right answers	-0.074	0.537	-0.034	2.87	1.23	0.89
<i>Design knowledge: Design problems must be framed</i>						
In design, the problem and the solution co-evolve, where an advance in the solution leads to a new understanding of the problem.	-0.001	0.004	0.818	4.47	0.63	0.52
Design, in itself, is a learning activity where designers continuously refine and expand their knowledge.	-0.051	-0.022	0.714	4.60	0.67	0.73
Design is as much a matter of finding problems as it is of solving them.	0.085	0.012	0.489	4.30	0.79	0.57

* Unique factor loading > 0.40 are in bold.

We conducted paired sample t-tests and two-way repeated measures ANOVA to measure the effects of using realistic design challenges on the three identified factors.

Design Skills Test

Previously, we developed a measure of problem framing ability that we have shown provides valid information about students' design problem framing skills for instructors interested in teaching with and refining design challenges [Blind for review23]. The measure is an individually-completed performance-based assessment that includes an authentic design problem in a 1-page brief and three dimensions of a coding scheme adapted to the specifics of the problem: problem requirements [12, 21, 24, 25], design practices [24, 26, 27], and design style [28-32]. Students complete the measure in 15 minutes in class and typically fill one page with text and sketches. We used the same version—in which students are presented with the issue that while dirty plates sit in a dishwasher, bacteria grow, causing an unpleasant smell—as a pre-post measure in the first and senior years (Table 1), collecting baseline and implementation data.

Previously, we refined the coding scheme, omitting codes that were difficult for independent coders to agree on (Tables 4-5) [23]. We used contrast codes to *characterize* but not *evaluate* the student work; thus, a negative number should not necessarily be viewed as poor performance, but rather reflect a tendency to not exhibit a specific approach. Two independent coders scored 20% of the work and resolved any disagreements.

Table 4. Coding scheme part 1: design requirements—factual and conceptual codes used in framing the problem, including attending to constraints and considering need outlined in the design brief. Coders are also asked to note ambiguous situations.

Code	Description	Value 1	Value 0	Value -1
Cheap	The device must be "cheap" is stated. Synonyms okay, but must be stated, not interpreted/implied.	Stated clearly, including synonyms	Not violated, but not mentioned or not mentioned clearly	Obvious violation of this constraint
No residue	The design must not leave a residue. Some students plan for a way to wash a residue off and this counts. Others talk about it as being safe, which is the core idea behind no residue. Synonyms okay, but must be stated, not interpreted/implied.			
No inherent smell	The design must not have it's own smell or perfume or way to cover bad odors. Synonyms okay, but must be stated, not interpreted/implied.			
Autonomous	The design must work autonomously, without needing to be turned on/off and without adding cleaning agents. Synonyms okay, but must be stated, not interpreted/implied.			
Needs: Reduce Odor	The main need is something to reduce odor to barely perceptible level	Mentions odor or suggests need to measure	Mentions vaguely	No direct mention of odor
Needs: Dirty Dishes	The need is tied to dirty dishes	Dirty dishes mentioned	Mentions indirectly as source of food or bacteria	No dirty dishes referenced

Table 5. Coding scheme parts 2—design practices, such as generating ideas and considering stakeholder perspectives, and 3—design style.

Code	Description	Value 1	Value 0	Value -1
Roles	People who use the dishwasher, service it, manufacture it are mentioned.	At least one person is mentioned clearly	No direct mention of specific people, but "you" is mentioned; do not include "I", "we" or "us"	No mention of people, directly or indirectly
Use-case	Describes how the design is used, envisions use; even if use is in violation of constraints, whimsical, wrong or you think it won't work. For simple designs, judge on whether you can envision use, even if that use is simple.	Vivid or clear description with details, even if constraints are violated. Easy to picture, even if design is simple	A bit vague description of use, hard to picture or major gaps in use	No sense of how design would be used
Ideation	Multiple ideas presented. The ideas are not rehashing or restating of the problem, but instead are ideas generated by the student, either about the problem or possible solutions. They may be set as questions or as a set of unknowns needing to be resolved, or a group of possible solutions/solution paths.	More than one clear idea is present that was not already stated in the problem	One clear idea is present that was not already stated in the problem	No ideas present that were not already stated in the problem
Scaffolding to solution	Experienced designers plan steps toward solution. Novice designers jump to solution prior to understanding the problem.	Puts forth multiple, specific steps toward solution including describing the problem	Mentions vague or unclear/not feasible steps, or just one specific step	No steps put forth or goes straight to the solution
Diagram function	Diagram depicts function of design or how system works. Even in relatively passive designs, components interact actively (including chemical reactions, physical actions, etc.). Count text linked to diagram directly, but not captions.	Diagram depicts function or system by including arrows showing movement of material or energy OR action verbs that describe what a part does ("to spray"; "sprays" "spraying") or a "graphic" verb (a spray of water is drawn)	Diagram may depict arrows that point at components but that don't depict movement/flow /action, components may be listed but are not shown functioning, or diagram may omit any of these	No diagram
Diagram context	Diagram depicts design context	Diagram depicts detailed context with at least two elements of the design	Diagram depicts iconic or simple context, or labels stand in for context	No diagram
Organized response	Student response is organized, includes headings, bulleted or numbered lists	Includes headings, divides response into sections clearly, (e.g. problem, constraints, etc.; conceptual sections)	Includes a list or simple organizational marker. Overall, not clearly organized a priori or conceptually	No clear markers of organization, though writing may be organized

We calculated descriptive statistics and compared frequencies of codes, first to determine if there was a difference between groups of first year students at the initial assessment point. We performed paired samples t-tests and two-way repeated measures ANOVA to address the second and third research questions.

Results

Research question 1: To what extent do realistic design challenges affect students' design self-efficacy and explicit design knowledge?

Our first research question investigated the extent to which realistic design challenges (Table 2) affected students' design self-efficacy and explicit design knowledge. Using paired sample *t*-tests (Table 6), and two-way repeated measures ANOVA (Table 7), we found that students in both baseline and implementation reported moderate design self-efficacy, with post-course scores slightly but significantly higher. We did not find differences by group or time point on students' knowledge of design problems as ill-structured. By the end of the course, compared to the baseline, students in the implementation group reported somewhat lower understanding that design problems must be framed, but this difference was not statistically significant.

Table 6. Means (SDs) of design self-efficacy, ill-structuredness, and framing at the semester start and end. Significant differences are bolded.

	Semester Start (Pre)			Semester End (Post)		
	Design self-efficacy	Ill-structuredness	Framing	Design self-efficacy	Ill-structuredness	Framing
Baseline group (n=62)	3.41 (.77)	3.75 (.78)	4.49 (.48)	3.70 (.82)	3.73 (.90)	4.57 (.57)
Implementation group (n=63)	3.53 (.76)	3.67 (.93)	4.42 (.60)	3.60 (.90)	3.46 (.98)	4.25 (.80)

Table 7. Two-way repeated measures ANOVA for design self-efficacy and explicit design knowledge constructs, ill-structuredness and framing. Significant differences are bolded.

Source of variance	SS	df	MS	F	p	η^2
Design self-efficacy						
<i>Between-subject effect</i>						
Base. vs. Impl. (A)	.00	1	.00	.01	.95	.00
Error	114.66	123	.93			
<i>Within-subject effect</i>						
Semester Start/End (B)	1.93	1	1.93	5.03	.03	.04
A*B	.79	1	.79	2.05	.16	.02
Error	47.10	123	.38			
Ill-structuredness						
<i>Between-subject effect</i>						
Base. vs. Impl. (A)	1.90	1	1.90	1.50	.22	.01
Error	155.85	123	1.27			
<i>Within-subject effect</i>						
Semester Start/End (B)	.89	1	.89	2.43	.12	.02
A*B	.57	1	.57	1.54	.22	.01
Error	45.04	123	.37			

Framing						
<i>Between-subject effect</i>						
Base. vs. Impl. (A)	4915.04	1	4915.04	10337.50	.000	.99
Error	58.48	123	.48			
<i>Within-subject effect</i>						
Semester Start/End (B)	.15	1	.15	.52	.47	.00
A*B	.98	1	.98	3.27	.07	.03
Error	36.70	123	.30			

Research question 2: In what ways do first year students approach framing design problems?

The second research question focused on the ways first-year students approach framing design problems, prior to design instruction. Overall, across semesters, first-year students were likely to mention the need to reduce odor and to begin generating ideas (Figure 1). They were unlikely to mention relevant roles, to organize their responses, and few included diagrams. We found diversity in the approaches taken by first-year students, and thus we also investigated patterns in co-occurring codes. Some students leapt right to solutions, while others approached framing by listing design requirements mentioned in the design brief, especially noting that it must be cheap, leave no residue, and have no inherent smell to address the problem of reducing odor (Figures 2 & 3). Others focused on the underlying cause—dirty dishes—and tended to generate ideas about possible solutions, generally without including diagrams. For those who did organize their response, this tended to be in the form of bulleted lists as they generated ideas.

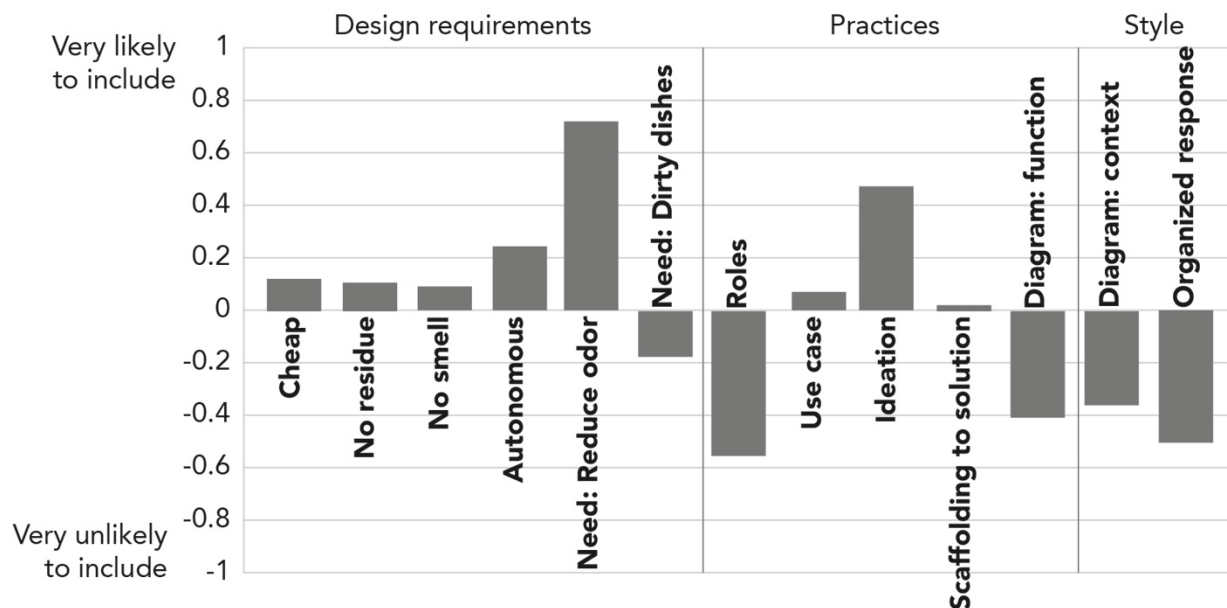


Figure 1. Mean scores across all first-year design skills tests competed at the beginning of the course.

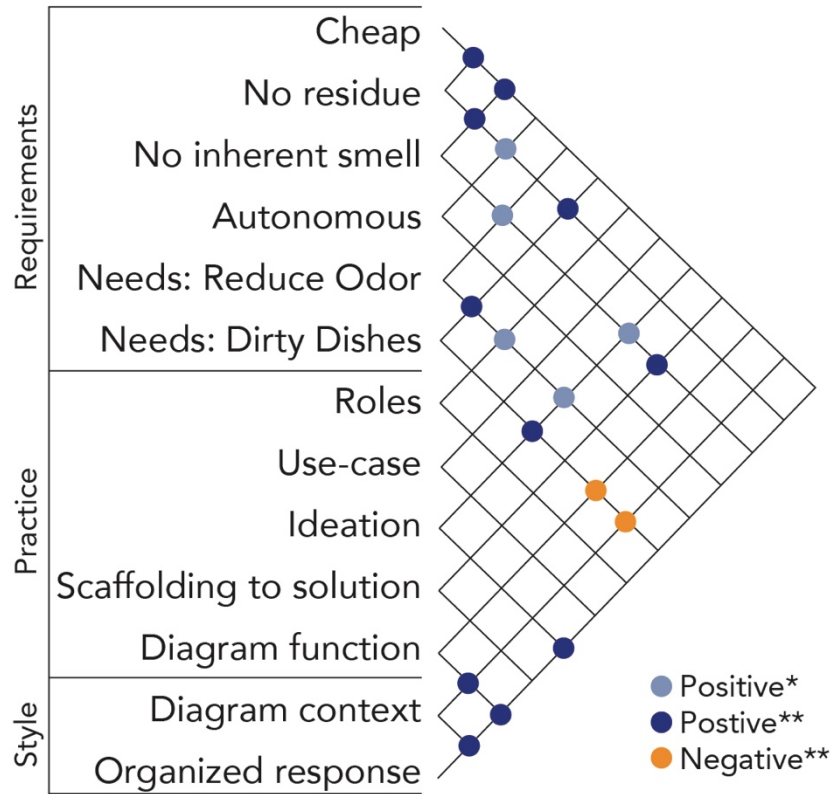


Figure 2. Significant correlations between codes. **Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed).

Listing design requirements approach

- last 10 years
- cheap
- no residue
- not sensitive to water
- no smell
- easy to use
- no maintenance

Solution-first approach

add a material that absorbs the odor to the walls of the dishwasher, or something that would eat away and deteriorate by the by product of the odors such as the sulfur compounds and aromatic compounds. if the layer of this material is thick enough you should be able to have it for 10 years

Beginning from underlying cause approach

As clients wait for there to be a full load of dishes. Instead of wasting water to clean only a few, the dirty dishes start to smell due to the food residue. In order to avoid the odor more permanently than using a cleaning solution, I would find a chemical that would begin to break down the food and bacteria from the dishes. Like toilets that use water when you flush I would find a solution so the washer machine could clean itself with a touch of a button.

Figure 3. Examples of typical approaches

Research Question 3: Compared to a baseline group, how do first year students who have experienced realistic design challenges approach framing design problems?

Our third research question compared the problem framing approaches of two groups of first-year students—those enrolled in the original lecture-based course (baseline) and those enrolled in the design challenge-based course (implementation). We found that compared to the baseline group, the implementation group showed more changes overall from their initial work to their final work. Paired samples *t*-tests comparing differences in gain scores showed statistically significant differences for the following: No residue, Autonomous, Needs: Dirty dishes, Use case, Scaffolding to solution, Diagram function and Diagram context (Figure 4).

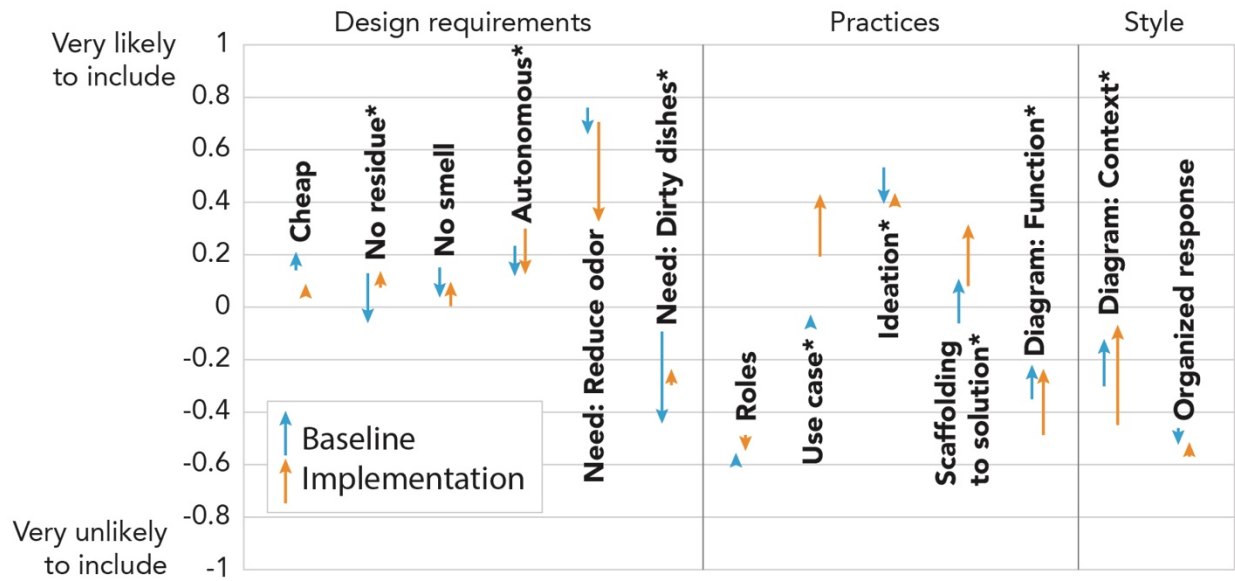


Figure 4. Gain scores for each code in the baseline and implementation groups. Arrow indicates direction of change.

We ran a two-way repeated measures ANOVA (Table 8). Our main interest is differences between pre- and post-test in the two different groups; therefore, we focused on the interaction effects, finding four significant areas: No residue ($F(1, 206)=9.94, p < .01$ with $\eta^2 = .046$), Needs: dirty dishes ($F(1, 206)=3.69, p < .10$ with $\eta^2 = .018$), Use case ($F(1, 206)=5.68, p < .05$ with $\eta^2 = .027$), and Ideation ($F(1, 206)=8.98, p < .01$ with $\eta^2 = .042$). Specifically, by the end of the course, the baseline group was significantly less likely to frame the problem in light of certain requirements (no residue, and the underlying cause, dirty dishes); the implementation group was significantly more likely to provide a use case and to provide details about the next steps to take to get to a design solution.

Table 8. Results of repeated measures ANOVA for significant interactions. Significant differences are bolded.

Source of variance	SS	df	MS	F	p	η^2
Two-way repeated measures ANOVA for No residue						
<i>Between-subject effect</i>						
Base. vs. Impl. (A)	.54	1	.54	4.46	.04	.02
Error	25.00	206	.12			
<i>Within-subject effect</i>						
Pre/post test (B)	.45	1	.45	4.59	.03	.02
A*B	.97	1	.97	9.94	.00	.05
Error	19.99	206	.10			
Two-way repeated measures ANOVA for Need: Reduce odor						
<i>Between-subject effect</i>						
Base. vs. Impl. (A)	3.81	1	3.81	6.88	.01	.03
Error	113.92	206	.55			

<i>Within-subject effect</i>						
Pre/post test (B)	4.82	1	4.82	14.57	.00	.07
A*B	1.88	1	1.88	5.68	.02	.03
Error	68.18	206	.33			
<i>Two-way repeated measures ANOVA for Need: Dirty dishes</i>						
<i>Between-subject effect</i>						
Base. vs. Impl. (A)	.00	1	.00	.00	.97	.00
Error	121.91	206	.59			
<i>Within-subject effect</i>						
Pre/post test (B)	2.37	1	2.37	6.19	.01	.03
A*B	3.43	1	3.43	8.98	.00	.04
Error	78.79	206	.38			
<i>Two-way repeated measures ANOVA for Use case</i>						
<i>Between-subject effect</i>						
Base. vs. Impl. (A)	13.33	1	13.33	32.16	.00	.14
Error	85.40	206	.46			
<i>Within-subject effect</i>						
Pre/post test (B)	1.41	1	1.41	6.25	.01	.03
A*B	.83	1	.83	3.69	.06	.02
Error	46.40	206	.23			
<i>Two-way repeated measures ANOVA for Ideation</i>						
<i>Between-subject effect</i>						
Base. vs. Impl. (A)	.23	1	.23	.73	.40	.00
Error	65.14	206	.32			
<i>Within-subject effect</i>						
Pre/post test (B)	.29	1	.29	1.14	.28	.01
A*B	.56	1	.56	2.20	.140	.01
Error	52.10	206	.25			

Conclusion and Future Directions

In this study, we adopted a multidimensional approach to understand the development of design self-efficacy and implicit and explicit design knowledge for first year students enrolled in an introductory chemical engineering course, contrasting versions of the course that did or did not include realistic design challenges. First, we found a small but significant increase in design self-efficacy, regardless of which version of the course students enrolled in. This finding is in contrast with past research [7, 9]. Our findings may differ due to the nature of the population, which includes a high proportion of first generation students, and may reflect a general increased confidence in college skills. Alternatively, as research has shown alignment between students' reports of self-efficacy following experience building related skills [6], it is possible that students in the baseline group expressed greater confidence simply as a result of completing the course, whereas those who completed the realistic design challenges provided more informed reports of their design self-efficacy. Given these findings, we would caution others against using self-efficacy as a measure without also measuring other indicators of learning and development.

In terms of explicit design knowledge, we found that while students in the baseline group showed no appreciable difference, students in the implementation group showed a small but

insignificant decrease in knowledge of design problems as ill-structured and as requiring framing. As this contrasts with past research showing increases in explicit rather than implicit design knowledge [22], we plan to investigate the impact of minor changes to the curricula that foster the development of both forms of knowledge. For instance, adding brief reflective prompts that encourage students to connect their design work to explicit design knowledge may help. For instance, we will explore whether the following prompts, given as exit tickets and end-of challenge reflections, support this connection:

- Ill-structured exit ticket: Design problems, unlike problems you may have worked on in your science and math classes, often have many unknowns, and different designers fill in gaps differently from one another. What are some unknowns right now? What are different ways members of your team have filled in gaps in knowledge?
- Framing exit ticket: What did your team do today that changed how you are framing the design problem?
- Ill-structured end-of-challenge reflection: Design problems, unlike problems you may have worked on in your science and math classes, have many possible solutions. Describe some of the different ideas and solutions you heard about from your peers.
- Framing end-of-challenge reflection: Looking back at how you thought about the problem at the beginning of the challenge, how have you reframed the design problem?

In contrast to past research [19-22], we found that first year students who completed realistic design challenges developed implicit design knowledge [15-17]. The baseline group students, who heard technical lectures and participated in team-building challenges and a deterministic problem were significantly less likely to frame the problem in light of key requirements (no residue, and the underlying cause, dirty dishes) by the end of the course. In contrast, by the end of the semester, following design instruction, the implementation group was significantly more likely to provide a use case and to provide details about the next steps to get take to get to a design solution. The design challenges in the implementation group included supports for framing design problems, pitching solutions in terms of use cases, and scaffolded students in their design process. Results suggest that additional supports for considering various stakeholder roles may be warranted. For instance, future versions could include an assignment that involves listing possible stakeholders and identifying ways their needs relate to possible design solutions. By contrasting the two groups, the differences in their approach to framing design problems also suggests increased capacity to treat design problems as needing to be framed by considering contexts of use as well as understanding of the complex work involved in solving ill-structured problems [18].

By examining how students with no formal design education approached design problems, we also identified a promising foundation for those who teach design. We observed varied patterns in how students approached accessible yet authentic problems in the *design skills test*. While few considered roles or included diagrams, many attended to needs and began by generating ideas. This is a promising start to ill-structured design problems and reinforces that, by providing accessible yet realistic design challenges, first year students are ready to develop as designers.

Taken together, these results suggest that first-year students can learn to design before they acquire knowledge about design, and demonstrate their readiness for working on realistic design challenges. Future research will investigate addition refinements to enhance the development of

explicit design knowledge. Likewise, further research will investigate the interactions between design self-efficacy and implicit and explicit design knowledge.

Acknowledgment

This material is based upon work supported by the National Science Foundation under Grant No. #1623105. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We also thank the students who participated in initial coding efforts.

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